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Implications of changes in the Northern Hemisphere circulation for the detection of anthropogenic climate change

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Abstract. The first principal component of Northern Hemisphere sea level pressure, known as the Arctic Oscillation (AO) index, has increased significantly in recent winters, and this change is associated with ~30% of Northern Hemisphere January-March warming. We examine the AO in a model used to detect anthropogenic influence on climate, and find that it exhibits no systematic trend in response to greenhouse gas, sulphate aerosol, or ozone forcing. To test the significance of this discrepancy for anthropogenic climate change detection, we include the spatio-temporal pattern of temperature change associated with the observed AO in the set of forcing-response "fingerprints" used to account for observed changes, thus separating temperature change associated with the AO from a residual. We find that the detection of a global response to both anthropogenic greenhouse gases and sulphate aerosols is robust to this exclusion of AO-related warming.

Introduction

The leading mode of month-to-month variability in the Northern Hemisphere is an approximately zonally symmetric pattern known as the Arctic Oscillation, or AO [*Thompson and Wallace*, 1998], whose temporal evolution closely resembles the more regional North Atlantic Oscillation (NAO). The AO emerges as the leading empirical orthogonal function (EOF) of cold season sea level pressure (SLP) in the Northern Hemisphere, and is strongly coupled to variations in surface temperature [e.g. *Rodwell et al.*, 1999], and the strength of the stratospheric polar vortex [*Baldwin and Dunkerton*, 1999]. Observations indicate that there has been a significant trend towards the positive index phase of the AO since the 1960's, corresponding to a decrease in pressure over the pole [*Thompson et al.*, 2000]. This change is associated with a warming over the Eurasian landmass, and in the JFM quarter accounts for slightly over half the warming trend observed in this region, or about 30% averaged over the Northern Hemisphere as a whole [*Hurrell*, 1996; *Thompson et al.*, 2000]. There is as yet no consensus on the causes of the observed change in the AO: Greenhouse gas forcing [*Shindell et al.*, 1999; *Fyfe et al.*, 1999] and stratospheric ozone depletion [*Volodin and Galin*, 1999] have both been suggested, while unforced variability remains a possibility [*Wunsch*, 1999].

Tett et al. [1999] examine the influence of natural and anthropogenic forcings on the climate system, using the HadCM2 model [*Johns et al.*, 1997] to estimate internal variability and patterns of response to external forcing. After signal-to-noise optimisation these patterns are referred to as "fingerprints" [*Hasselmann*, 1997; *Hegerl et al.*, 1997; *Allen and Tett*, 1999]. They detect the response to both anthropogenic greenhouse gases and sulphate aerosol over the last five decades at the 95% confidence level. However, their conclusions depend on the realism of the model simulation of both forcing-response patterns and internal variability. *Shindell et al.* [1999], *Corti et al.* [1999], and *Palmer* [1999] all draw attention to potential problems in climate change detection and prediction if the response of atmospheric circulation regimes to external forcing is unrealistically simulated in the climate model used. If the model underestimates the change in the AO, then the observed AO change, the origin of which remains unproven, will project onto the fingerprint of anthropogenic climate change, leading to an overestimate of the amplitude of the anthropogenic signal. It is this problem that we seek to address here.

Comparison of the modelled and observed Arctic Oscillation

Figure 1a shows the first EOF of the November-April monthly mean sea level pressure anomalies [*Trenberth and Paolino*, 1980] for the years 1947–1997 over the region northward of 20°N: This is the Arctic Oscillation pattern, as defined by *Thompson and Wallace* [1998]. It is characterised by a polar minimum surrounded by a zonal ring of oppo-

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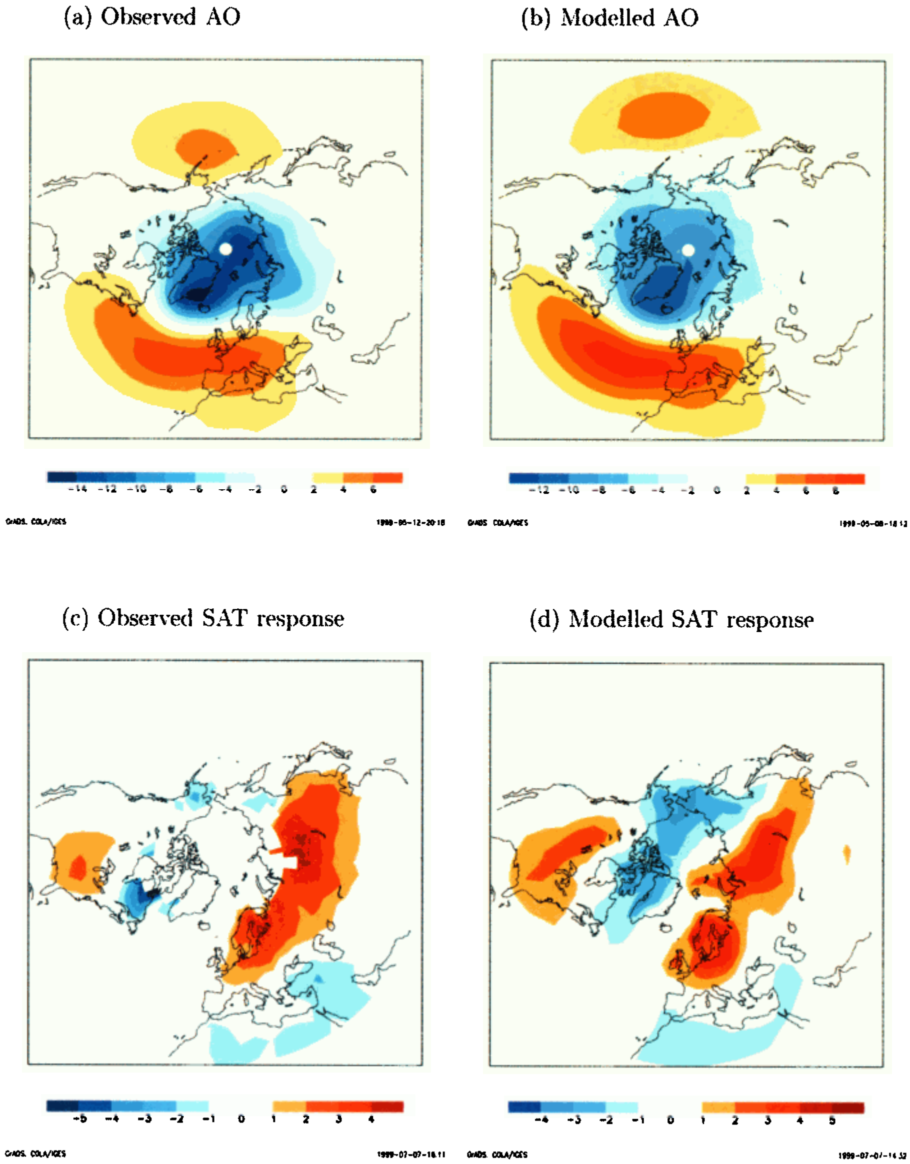

Figure 1. The upper panels show the first EOF of NDJFMA SLP northward of 20°N in the observations (**a**) and HadCM2-CTL (**b**) (dimensionless). Panel **c** shows the regression pattern of monthly mean surface air temperature on the observed AO index for DJF monthly means, and panel **d** shows the corresponding pattern in the model (K/hPa). The pressure anomaly plotted in **a**(**b**) in hPa is associated with the temperature anomaly **c**(**d**) in K.

site sign, and it is largely zonally symmetric. The model AO pattern (figure 1b), derived in the same way from 99 years of HadCM2 control, is generally similar, but has a broader polar minimum and a stronger North Pacific lobe, consistent with the findings of *Osborn et al.* [1999]. AO temperature response patterns were derived separately for each season by regressing monthly-mean 1.5m air temperature [*Parker et al.*, 1994] onto the corresponding AO index (obtained by regressing monthly-mean SLP onto figure 1a). Both the index and temperatures were high-pass filtered at 10 years to give the temperature response characteristic of the AO on sub-decadal timescales. The observed DJF temperature response (figure 1c), and the modelled temperature response (figure 1d), derived in the same way as the observed regression pattern, are similar, and largely consistent with advection of warm maritime air onto the continents and cold continental air onto the ocean.

The results shown in figure 1 indicate that the model's AO is generally spatially realistic, but they tell us nothing about its response to external forcing. *Thompson et al.* [1999] use Student's t-test to show that the linear trend over 30 years in the observed AO index is significantly greater than zero at the 95% level in December, January and February, even if auto-correlation is taken into account. For the climate change detection problem, the crucial question is not whether the trend in the AO is significant against some noise-based null-hypothesis, but whether it is consistent with the corresponding simulations of the climate model. Annual and seasonal means of observed SLP for the years 1900–1995 were projected onto the AO pattern shown in figure 1a to give AO indices. Corresponding indices were derived for 1091 years of HadCM2-CTL using the model's EOF. The model AO was, if anything, found to be too active on sub-decadal timescales, having 1.2 times the observed variance in the DJF mean. In contrast, when observed AO trends over intervals from between 10 and 60 years ago to the present were compared with ranges of trends in equal-length intervals extracted from the HadCM2 control integration, as in *Osborn et al.* [1999], the recent observed DJF AO trends lay well outside the 5%-95% range of control variability for interval-lengths around 20 and 28–46 years (figure 2), although trends in the annual means were consistent. These results show that the observed DJF trend is inconsistent with control variability on some timescales, suggesting either that the real atmosphere has more low frequency internal variability in the AO than the model, or that the observed AO index is increasing because of some external forcing. However, we found that AO trends in ensembles of HadCM2 runs forced with greenhouse gases and sulphate aerosol (GS), and greenhouse gases, sulphate aerosol and stratospheric ozone depletion (GSO) are in no case significantly different from zero over the period of the observations, as for the greenhouse gas only runs [*McDonald*, pers comm]. Moreover, the recent observed AO trend was found to be significantly greater than simulated trends in both GS and GSO simulations for trend-lengths of 28–42 years, using a *t*-test based on control variability (shown by a bold line in figure 2). Thus our results indicate that HadCM2 does not show a response to anthropogenic forcing comparable to the AO change observed, in agreement with the results of *Shindell et al.* [1999] for a model with only two stratospheric levels (HadCM2 has around six levels in the stratosphere).

The implications for the detection of anthropogenic climate change

The HadCM2 model has been used extensively in climate change detection studies both to estimate forcing-response patterns of temperature change, and to estimate natural variability [e.g. *Allen and Tett*, 1999; *Tett et al.*, 1999]. *Shindell et al.* [1999] correctly observe that such detection results may be unreliable if the model used does not simulate a realistic trend in the AO. To address this concern, we examined the implications of including a fingerprint representing temperature change due to the observed AO change in the set of forcing-response patterns used to explain observed surface temperature anomalies in an optimal fingerprinting exercise otherwise identical to *Tett et al.* [1999]. We thus disregard any AO-related temperature change in the estimate of the amplitude of the anthropogenic signal. We reiterate that our aim was not to explain the discrepancy between modelled and observed AO trends, but to quantify the implications of this discrepancy for recently-reported detection and attribution results. We reconstructed spatio-temporal fingerprints associated with the AO by multiplying the observed temperature regression patterns (figure 1c for DJF), by decadal means of the associated observed AO index for the years 1946–1995. We then applied the optimal fingerprinting methodology described in *Allen and Tett* [1999] treating the AO temperature response pattern exactly as the other forcing-response fingerprints, and using the same T4 spherical harmonic truncation [*Stott and Tett*, 1998] and 10 EOF truncation as *Tett et al.* [1999].

Using the residual test detailed in *Allen and Tett* [1999], we were able to reject the hypothesis that the observed change in temperature is explained solely by the observed AO change and other internal variability in annual, DJF and MAM means, whereas both GS and GSO patterns do provide an adequate explanation. Thus AO-related temperature changes cannot fully explain the recent record, but they could still impact on the detectability of individual signals. *Tett et al.* [1999] report that both greenhouse gas and sulphate components of the anthropogenic signal are simultaneously detectable in a two-way regression: Best-guess amplitudes are positive in both cases, and the confidence intervals in figure 3 do not intersect either axis. When the AO temperature pattern was included, and a three-way regression was performed, the greenhouse gas and sulphate aerosol signals were still detected at the 95% confidence level (triangles in figure 3). As expected, the uncertainties are somewhat larger, since we are disregarding all information in the

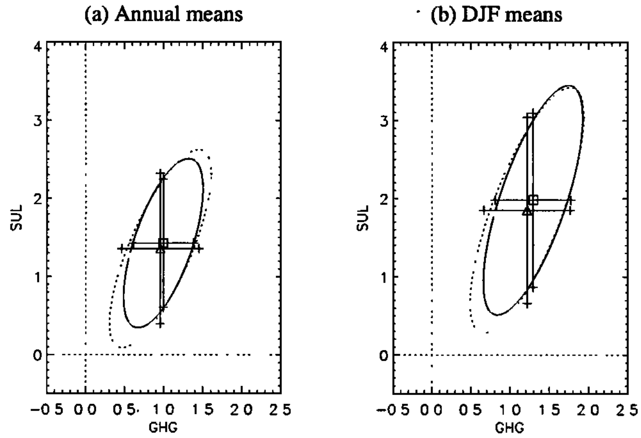

Figure 3. Ellipses containing 90% of the estimated joint distribution of amplitudes of greenhouse gas (GHG) and sulphate aerosol (SUL) signals in a two-way regression (solid lines), and in a three-way regression with the observed time-space AO fingerprint (dashed lines). The square and triangle represent the respective best-fit values. Error bars indicate 5%-95% one-dimensional confidence limits.

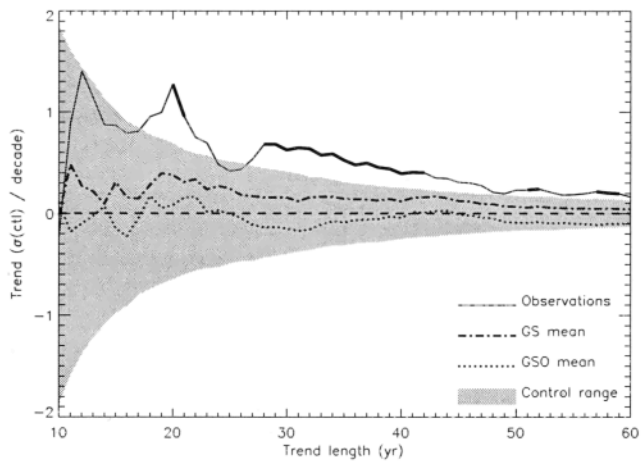

Figure 2. A comparison of the trend in the observed Arctic Oscillation index for DJF with the corresponding trend in HadCM2. The solid line shows the observed trend as a function of the length of time over which it is measured, always ending in 1997, and in bold where significantly different from both GS and GSO at the 95% level. The grey band shows the 5%-95% range of trends seen in 1091 years of HadCM2-CTL, and the dashed lines show ensemble mean trends for GS and GSO.

direction of the AO response, but enough information remains for both anthropogenic signals to be detectable.

If we restrict our analysis to the Northern Hemisphere, the combined response to greenhouse gases and sulphate aerosols remains detectable in a two-way regression including the AO pattern, but the individual greenhouse and sulphate signals are no longer distinguishable in a three-way regression. This is to be expected, since the main feature distinguishing the greenhouse and sulphate signals is the inter-hemispheric contrast. Note that positive Antarctic Oscillation trends in the Southern Hemisphere should have very little influence on Southern Hemisphere temperature in the regions with sufficient coverage to be used for detection [*Thompson et al.*, 2000].

Conclusion

The SLP signature of the unforced AO and its associated temperature response pattern are generally well-simulated in HadCM2, although the polar SLP minimum is broader in the model than in the observations. A comparison of trends in the DJF AO index indicates that the observed trend over the last 20 and 28–46 years is inconsistent with natural variability, as simulated by HadCM2. This trend in the AO has been attributed to external forcing, either by greenhouse gases or ozone depletion. However, if such a forcing mechanism exists, then it is not well-simulated by HadCM2, since ensembles forced with observed greenhouse gases, sulphate aerosol, and ozone depletion showed no significant trend over the same period as the observations.

It has been suggested that recent detection and attribution studies such as *Tett et al.* [1999] may be invalidated by such a model deficiency in simulating the Arctic Oscillation [*Shindell et al.*, 1999]. However we find that the main results of *Tett et al.* [1999] are reproduced even if temperature changes associated with the AO change are explicitly disregarded. In particular greenhouse gas and sulphate aerosol signals are still detected globally at the 95% confidence level in the 1946–1996 period. This implies that there is an important component of the temperature response to these anthropogenic forcings which is distinct from that associated with the AO.

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